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ABSTRACT

Annual rings are not commonly produced in tropical trees because they grow in a relatively aseasonal environment. However, in the subalpine zones of Hawai'i's highest volcanoes, there is often strong seasonal variability in temperature and rainfall. Using classical dendrochronological methods, annual growth rings were shown to occur in *Sophora chrysophylla*, commonly called māmane, a native tree species on Maunakea, Hawai'i. Sampling occurred at three sites on various facing slopes of Maunakea – Pu'ulā'au (west), Pōhakuloa (south), and Pu'umali (north). Chronologies established from nearby non-native, live conifer trees were used to verify the dates from a total of 52 series from 22 *S. chrysophylla* trees of the Pōhakuloa site, establishing an 86-y chronology (1926-2011) with 2003 rings, 0.255 mean series intercorrelation, 0.096 chronology lag-1 autocorrelation, and 0.303 mean sensitivity. Ring-width patterns were significantly correlated with monthly rainfall from August of the previous year at the Pōhakuloa site ($r = 0.377$, $P = 0.019$). This study is the first in the eastern tropical Pacific region to utilize dendrochronological methods to gain a better understanding of the growth dynamics of a native forest tree.

INTRODUCTION

When trees form annual growth rings, the ring patterns can be used to gain information on the stand history and growth rates of a particular forest ecosystem and to better understand past climate variability (Fritts 1976, Speer 2010). Annual rings develop as a consequence of intra-annual variability in suitable growing conditions, such as those related to monthly temperature or precipitation, and the amount of cambial growth depends on the length and timing of the appropriate climatic conditions (Fritts 1976, Stokes & Smiley 1968).

The existence of annual tree-rings is well-established in temperate and semi-arid forests with strong temperature seasonality. However, until recently, tropical forests were viewed as places that were very difficult, if not impossible, to conduct tree-ring research (Jacoby 1989, Worbes 1995). Tropical trees were long considered to lack annual rings due to the presumed uniform tropical climate with a general lack of seasonality. However, there is considerable variability in the climate in the tropics, with the majority of the tropics experiencing some climatic seasonality, particularly for precipitation. Many studies have demonstrated that some of the tree species growing in tropical areas with a predictable dry season or seasonal flooding produce annual growth rings (Baker *et al.* 2005, Fichtler *et al.* 2004, Schöngart *et al.* 2004, Worbes 1999, Worbes *et al.* 2003). Fichtler *et al.* (2003) demonstrated that annual rings are even present in certain species growing in an everwet (non-seasonally wet) tropical rain forest.

Subalpine habitats in Hawai'i are considered highly vulnerable to the effects of climate change, and understanding climate trends at high elevations is important for

validating climate models and for protecting at-risk native species and communities (Giambelluca & Luke 2007). Tree-ring studies have not yet been conducted in Hawaiʻi, however they are of considerable potential significance for two reasons. First, Hawaiʻi's native forests support a globally unique and highly threatened endemic flora and fauna. Second, the eastern tropical Pacific region is an area of global relevance for regional and global climate dynamics due to the role of the El Niño-Southern Oscillation (ENSO) phenomenon. Long tree-ring records from the western Pacific have provided important insights into ENSO and ENSO-induced drought variability at decadal and centennial time-scales (D'Arrigo *et al.* 2008, Fowler 2008). No such records exist for the eastern dipole of ENSO, where ENSO variability initiates. In January 2010, we began exploring the slopes of Maunaloa and Maunakea on the island of Hawaiʻi searching for possible candidate tree species that could be studied using tree-ring dating methods. The most promising of the tree species examined was *Sophora chrysophylla*, commonly called māmane, a native tree that is dominant in these subalpine ecosystems and has long been known to produce rings. The primary goal of this study was to determine if these rings are produced annually, and if so, to develop a tree-ring chronology for *S. chrysophylla* on the slopes of Maunakea. A second goal was to use the tree-ring chronology to explore the relationship between ring-width patterns and rainfall variability of this ecologically important species.

STUDY SITE

Three sites within subalpine woodland on Maunakea volcano were chosen for collecting *S. chrysophylla* samples (Figure 1). The Pōhakuloa site is located on the southern slope (19°44'4" N, 155°30'1" W) with an altitudinal range of 2045-2100 m asl, and was burned in a fire in August 2009. The Puʻulāʻau site is located on the western slope (19°50'4" N, 155°34'4" W) with an altitudinal range of 2200-2785 m. The Puʻumali site is located on the northern slope (19°53'57" N, 155°26'16" W) with an altitudinal range of 2170-2370 m.

The climate of the subalpine woodlands on the slopes of Maunakea is seasonally variable, with frost occurring regularly from January to April (Juvik *et al.* 1993, Scowcroft 1983). Temperatures range from nighttime lows a few degrees below 0°C to daytime highs above 20°C with mean annual rainfall of 350-750 mm (Scott *et al.* 1984, Scowcroft & Conrad 1992, van Riper 1980). The wet season generally occurs from November to April and the dry season from May to October (Scowcroft 1983, van Riper 1980). The soils in the area are very fine, sandy loams formed from volcanic ash, sand, and cinders, resulting in low water-retention capacity (Scowcroft 1983, Scowcroft & Conrad 1992).

Approximately 22,000 ha of *S. chrysophylla* subalpine woodland occur on Maunakea, making this the largest remaining stand in the State of Hawaiʻi (Hess *et al.* 1999, Scowcroft 1983, Scowcroft & Conrad 1992, Scowcroft & Giffin 1983). Open woodlands of almost pure *S. chrysophylla* can be found on the eastern, northern, and western slopes of Maunakea, while the south and south-western slopes of Maunakea are dominated by a relatively dense, mixed woodland of *S. chrysophylla* and

Myoporum sandwicense, or naio (Scott *et al.* 1984, Scowcroft & Giffin 1983). The *S. chrysophylla* subalpine woodland on Maunakea provides the only remaining habitat for the endemic Hawaiian honeycreeper *Loxioides bailleui*, commonly known as the palila (Banko *et al.* 2002a, b). The developing seeds of the *S. chrysophylla* are a primary food source for the *L. bailleui*, as well as for the larvae of *Cydia* spp., a specialist moth (Banko *et al.* 2002a, b). The production of *S. chrysophylla* flowers and seed pods occurs seasonally along the elevational gradient with about 4 mo separating peaks in reproduction, while production within an elevation stratum varies greatly; as a result, this food source is available to the *L. bailleui* and the *Cydia* larvae throughout the year (Banko *et al.* 2002b). The seeds of the *S. chrysophylla* contain levels of quinolizidine alkaloids that are toxic and potentially lethal to vertebrates, but the *L. bailleui* and *Cydia* larvae are adapted to utilizing this food resource (Banko *et al.* 2002a). The specialized relationship that the *Cydia* larvae and the *L. bailleui* have with the *S. chrysophylla* makes their survival dependent on the health and persistence of the *S. chrysophylla* subalpine woodlands.

STUDY SPECIES

The genus *Sophora* (Fabaceae, subfamily Faboideae) comprises nearly 50 species that are widely distributed throughout many temperate, tropical, and subtropical regions (Cumbie & Mertz 1962, Wagner *et al.* 1990). Most *Sophora* species are woody, and include forms ranging from tall trees, to small, herbaceous plants, to perennial herbs (Cumbie & Mertz 1962, Wagner *et al.* 1990). *Sophora* is represented in Hawaiʻi by one endemic species, *S. chrysophylla,* or māmane, and can be found from near sea level to elevations >3000 m asl (Lamb 1981, Rock 1920, Wagner *et al.* 1990). It is scattered throughout dry shrublands and dry to mesic forests of the main islands and holds a dominant role in the composition of subalpine vegetation on East Maui and Hawaiʻi (Wagner *et al.* 1990). *S. chrysophylla* trees typically average less than 8 m in height, with a trunk up to 0.9 m in diameter (Lamb 1981, Rock 1913). The wood is hard, dense, heavy, smooth, and very durable (Abbott 1992, Handy & Pukui 1998). The heartwood is a deep brown, while the sapwood is light brown to pale yellow (Lamb 1981).

METHODS

Sampling methods

Increment cores from live trees are best used for tree-ring analysis when trees have distinct annual rings and concentric radial growth (Worbes 1995). Hawaiian trees at high elevations often grow asymmetrically, and the oldest portion of the trunk (first ring) is rarely located at the center (Hart 2010). During the preliminary phase of this study, several increment cores of *S. chrysophylla* from the Puʻulāʻau site were inspected, and the rings were not clearly defined under the microscope. Given this and the asymmetric growth habit of *S. chrysophylla*, it was necessary to inspect entire cross-sections to visually identify complete rings around the circuit of the stem.

We located and sampled naturally dead *S. chrysophylla* trees at Puʻulāʻau (n = 29), Puʻumali (n = 15), and Pōhakuloa (n = 15). Individual trees were randomly located within each site and a 3-6 cm thick cross-sectional disc was collected from each individual with the use of a chainsaw. Standard sampling protocols in dendrochronology involve collecting samples well below the first branches, but above any buttresses at the base of the tree (Speer 2010, Stokes & Smiley 1968). We made every effort to avoid sampling trees where there were obvious patterns of distorted growth. Most samples were obtained from tree trunks that were relatively round and where the majority of the bark was intact, which sometimes occurred several meters above the base of the tree. Samples were transported to the laboratory where the surfaces of the cross-sections were first leveled with an electric hand-held planer perpendicular to the growth of the trunk, then sanded using coarse grit sandpaper, and finally polished using increasingly fine (up to 600 grit) sandpaper.

6

With no known mortality dates of these trees (it is possible that some of those that burned at the Pōhakuloa study area were already dead) we explored the possibility of assigning calendar years to *S. chrysophylla* rings by crossdating the ring-width series to those of nearby populations of exotic conifers, which included *Pinus radiata*, *Pinus jeffreyi*, and *Cedrus deodara*. An increment borer was used to extract a continuous core of wood from the bark to the pith of these living conifer trees (Speer 2010, Stokes & Smiley 1968). Five trees of *P. jeffreyi* were sampled at 1775 m asl, and six trees of *P. jeffreyi* and three trees of *C. deodara* were sampled at 2275 m asl on the western slope of Maunakea. Ten trees of *P. radiata* were sampled at 2470 m asl on the northeastern slope of Maunakea. Two cores were collected from each tree. Cores were stored in plastic straws, and transported to the laboratory where they were later removed and fixed to wooden core mounts, and allowed to dry for at least 48 h in an air-conditioned room. Once dry, the cores were sanded using coarse grit sandpaper, and then polished using increasingly fine (up to 600 grit) sandpaper.

Crossdating methods

The ring boundaries of the *S. chrysophylla* cross-sections were visually identified, checked, and marked across three different radii that were drawn through the least disturbed sectors of the wood starting from the same innermost growth ring to the outermost distinguishable and visually cross-dated ring. The ring boundaries of the conifer cores were also visually identified, checked, and marked across the two subsamples from each sampled tree. Ring-widths were then digitally measured at a precision of 0.001mm using a Velmex Measuring System (Velmex, Inc.) and the MeasureJ2X computer software program (Speer 2010). Since the death dates of the *S.*

chrysophylla samples were unknown, ring-widths were measured with no connection to calendar dates, and the resulting tree-ring series were considered undated. Ring-widths from the conifer cores were measured as dated rings since they were extracted from live trees, and the growth ring closest to the bark was used as a reference date for the most recent growing season (2012). An additional eight dated *S. chrysophylla* tree-ring series from trees previously collected live from the Pōhakuloa area were included in the study to help establish calendar dates of the samples.

The raw data were then imported into Cofecha, a statistical software program that numerically verifies the accuracy of the crossdating (Grissino-Mayer 2001). Crossdating was first conducted within individual conifer cores and *S. chrysophylla* cross-sections. After crossdating within individual trees was verified, Cofecha was then used to check the crossdating within each site between the undated *S. chrysophylla* samples and the dated conifer samples. For the Pōhakuloa site, the dated conifer samples were first used to verify the dated *S. chrysophylla* series. Cofecha was then used to check the crossdating between the dated and undated *S. chrysophylla* samples. Based on results from the Cofecha output on within-site crossdating, the necessary adjustments were made in assigning calendar dates to the undated *S. chrysophylla* samples using the editing software program Edrm (Grissino-Mayer 2001). Updated raw ring-width data were then compiled for each site and re-checked in Cofecha for dating accuracy.

Analysis methods

Raw ring-width data were analyzed and a site chronology was developed for the Pōhakuloa site using ARSTAN, a software program that removes age-dependent and

non-climatic trends in the data through standardization (Cook 1985). A Friedman

variable span smoother with a variable-span sensitivity level set to nine (least flexible)

was used to detrend the tree-ring series; this data-adaptive option is useful in modeling

the growth curves of disturbed tree-ring series that do not evolve through time in a

homogeneous way, and leaves intact tree-ring variability at inter-annual to decadal time

scales (Friedman 1984). A robust (biweight) mean with bootstrap confidence limits

was then used to calculate the mean chronology. The running RBar, the average

correlation between series (a measure of chronology signal strength), was set with a 20-

y window and a 19-y overlap (Wigley *et al.* 1984). All other options were set to default.

Several measures can be used to assess the quality of a chronology. The mean

series intercorrelation refers to the average of all pair-wise correlation coefficients

between tree-ring series in a given collection. The mean sensitivity refers to the

average relative difference in ring-width from one year to the next. The autocorrelation

refers to the correlation of a given detrended tree-ring index with the tree-ring index in

the previous year. Tree-ring chronologies with low autocorrelation values are usually

associated with high values of mean series intercorrelation and mean sensitivity, and

tend to contain high frequency variance in the series and strong climate signals, which

is useful for climate reconstruction (Fritts 1976).

The resulting tree-ring index chronology was used to investigate the

relationship between local climate and annual growth patterns of the *S. chrysophylla*

from the Pōhakuloa site using the software program PCReg

(http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software). Local

precipitation data were gathered from a nearby rain gauge station at 1986 m asl

operated by the Hawaiʻi State Division of Forestry and Wildlife (SKN #107, 19°44'55"

N, 155°31'32" W), and spans from 1938-1976 (Figure 2) (Giambelluca *et al.* 2011). To help determine the month most critical for tree growth a Pearson correlation analysis was conducted to examine the relationship between the current year's tree-ring index and the monthly precipitation within the present year, as well as the previous year (1-y lag) (Fritts 1976).

RESULTS

Crossdating summary statistics

An 86-y chronology spanning 1927-2012 was established from six of the 24 conifer trees, which included one *P. jeffreyi* and three *C. deodara* from the higher elevation site on the western slope, and two *P. radiata* from the north-eastern slope of Maunakea. This chronology included 591 rings with a 0.631 mean series intercorrelation, 0.203 chronology lag-1 autocorrelation, and 0.331 mean sensitivity.

Due to the lack of clear ring boundaries in some *S. chrysophylla* cross-sections, it was only possible to crossdate a portion of the samples from two of the three study sites. Of the 29 *S. chrysophylla* cross-sections collected from Puʻulāʻau, 12 were internally crossdated, and of these nine were crossdated to the conifer chronology. Of the 15 cross-sections collected from Puʻumali, 12 were internally crossdated, and of these seven were crossdated to the dated conifer chronology. Crossdating of *S. chrysophylla* to the conifers from these two sites yielded low correlation values.

All 15 *S. chrysophylla* cross-sections collected from Pōhakuloa were internally crossdated. In addition, seven of the *S. chrysophylla* series from the dated collection crossdated well with the conifer chronology prior to the 1980's. Low correlation values resulted when the undated *S. chrysophylla* series was crossdated to the combined dated *S. chrysophylla* and conifer chronology. Assuming that the *S. chrysophylla* series from the dated collection had been crossdated correctly with the conifers, and excluding the low correlation values after 1980, a total of 45 radii from the 15 undated *S. chrysophylla* series were crossdated to the seven dated *S. chrysophylla* series, to establish an 86-y chronology spanning from 1926-2011. This chronology included

11

2003 rings with a 0.255 mean series intercorrelation, 0.096 chronology lag-1 autocorrelation, and 0.303 mean sensitivity. General summary statistics of the conifer and *S. chrysophylla* chronologies are outlined in Table 1.

Quality of the chronology and relationship between growth and climate

Individual raw tree-ring series (n = 52) and the mean of all the series from the 15 cross-sections and seven previously dated *S. chrysophylla* series from the Pōhakuloa site are presented in Figure 3. Figure 4 is the mean of the detrended ring-width series, which is the standardized site chronology.

RBar is a measure of the strength of the common growth signal within a standardized site chronology (Wigley *et al.* 1984). The RBar graph in Figure 5 shows a relatively strong common signal for the chronology, with the least amount of variation in signal strength, expressed by smaller error bars, from the 1970's to the late 1990's indicating a stronger common signal amongst the samples for that time period. Expressed Population Signal (EPS) is a measure of the common variability within a chronology in relation to sample depth (Wigley *et al.* 1984). A chronology with an EPS value ≥0.85 can generally be used for climate analysis (Wigley *et al.* 1984). As seen in Figure 5, the EPS values for the Pōhakuloa *S. chrysophylla* chronology are above the 0.85 level (thick, black line).

The Pōhakuloa site statistics include high mean series intercorrelation and mean sensitivity, and low autocorrelation values. The Pōhakuloa chronology has a high RBar value, as well as EPS values greater than 0.85. These statistics show high inter-annual variability and a strong common signal, which indicates the chronology's reliability as a proxy for climate change studies, as well as its usefulness in studying the ecology of *S.*

chrysophylla.

The correlations between local monthly rainfall and standardized chronology index for *S. chrysophylla* from the Pōhakuloa site indicate that precipitation in August of the previous year is the best predictor of growth ($r = 0.377$, P = 0.019) (Figure 6).

DISCUSSION

Crossdating is based on the presence of a common interannual variation in the periodic growth patternsof trees from a similar area due to a common set of growth-limiting factors most often related to climate. Trees that do not show any synchronization in the variation of growth patterns will not crossdate (Stahle 1999). The ability to crossdate multiple time-series within and among individual samples of *S. chrysophylla* provides strong evidence that the growth rings in *S. chrysophylla* are indeed annual. In addition, there are two signature rings in the *S. chrysophylla* chronology, 1953 and 1985, indicating a common response in growth in the population.

Stronger evidence for annual growth rings is provided when time-series of at least 50-100 y are crossdated or when the tree-ring chronologies match those of species with known annual growth rings (Stahle 1999). Although the Pōhakuloa chronology has several time-series that are at least 50 y in length, the argument for annual growth rings in *S. chrysophylla* on Maunakea can be further strengthened once the chronologies for the Puʻulāʻau and Puʻumali sites are established since there are many more samples from these sites that are likely older than 50 y.

Additional support that growth rings of trees are indeed annual and not just growth bands can be provided when trees of the same species at different locations in a given climate region are crossdated (Stahle 1999). Region-wide crossdating for *S. chrysophylla* can be attempted once the chronologies for the Puʻulāʻau and Puʻumali sites are established; however, it is possible that the climate at these sites is too different for crossdating to be successful.

Further evidence supporting annual growth rings is provided if the site chronology is strongly correlated with regional climatic data (Stahle 1999). *S. chrysophylla* growth at the Pōhakuloa site was found to be significantly correlated with rainfall that occurred in the previous August, indicating that stem radial growth is greatest in a year following an August with heavier rainfall (wetter August). Leaf flush also generally occurs by August, and there are few, if any, flowers and seed pods being produced during that time (P.C. Banko, pers. comm.).

As with other tropical hardwood tree species, the development of centuries-long tree-ring chronologies is quite challenging (Stahle 1999). Although some tropical tree species have annual growth rings, studying these trees is often complicated by complex wood anatomy, and annual rings may be clear in young trees with relatively large rings, but are often much more difficult to identify as trees age (Stahle 1999). Since the successfully crossdated trees at Pōhakuloa were younger compared to those of the other two sites, the growth rings in the cross-sections were relatively concentric, evenly formed, and well-defined, which may have resulted in the high interseries correlation values reported here. This may help explain the success of crossdating all of the Pōhakuloa samples to the bark. On larger (>20 cm diameter) samples, the portions of the wood with the distinguishable ring boundaries were usually found on the inner sections closer to the heartwood, which led to shorter time-series being measured and likely affected our ability to crossdate samples among sites. To strengthen the Pōhakuloa chronology it is imperative to find larger, older, or longer dead *S. chrysophylla* samples that would provide longer time-series for cross-dating and would also extend the chronology further back in time.

Anchoring the rings of *S. chrysophylla*, and other native tree species, to calendar dates to develop long chronologies may depend on establishing chronologies of species with known reliable annual growth rings (Stahle 1999). Conifers are often long-lived and produce reliable annual growth rings in many temperate areas. Interestingly, we found that many of the conifers growing in our study areas also produce annual growth rings. *P. radiata* sampled on the north side of the mountain was difficult to work with and produced very short series lengths. *P. jeffreyi* sampled at the lower elevation site on the west side of the mountain had very unclear ring boundaries, and could not be used. In comparison, *P. jeffreyi* sampled at the higher elevation site on the west side of the mountain had clearer ring boundaries compared to that of the lower elevation site. Growth rings are much clearer in the early part of tree growth, but tend to get pinched and more difficult to work with towards the bark. *C. deodara* from the higher elevation site on the west side of the mountain has very clear and distinct ring boundaries, and contributed the majority of the samples used to establish the anchoring chronology in this study.

The often squat, gnarled, and wind-blown aspect of many *S. chrysophylla* trees seems to belie their age. Our results revealed that samples from even our largest trees (up to 55.7 cm diameter) may be relatively young (<150 y). While this may diminish their usefulness as records for how climate has varied over the past centuries in this region of the Pacific, it does provide hope for the success of ongoing restoration efforts of these forests. That these trees grow somewhat more quickly than we previously assumed means that degraded *S. chrysophylla* forests can potentially be restored within only a few decades.

This project represents the first application of dendrochronology in a native Hawaiian forest ecosystem. Overall, dendrochronology provides another way for natural resource managers to expand their knowledge on the functioning of native forest ecosystems and to gather much-needed information to enable them to develop more effective management systems. Non-destructive methods of tree-ring dating will allow for the estimation of age and growth rates of other native Hawaiian tree species, and would allow for the development of growth models that can be used to assess the current state and project the future structure and composition of native Hawaiian forest ecosystems.

ACKNOWLEDGMENTS

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Table 1. General summary statistics of the conifer (*Pinus radiata, Pinus jeffreyi, Cedrus deodara*) and *Sophora chrysophylla* tree-ring chronologies on Maunakea, Hawaiʻi.

Statistic	*Pinus* and *Cedrus* spp.	*Sophora chrysophylla*
Time span	1927-2012 (86 y)	1926-2011 (86 y)
Number of cores (trees)	12 (6)	52 (22)
Number of rings in series	591	2003
Median length of series (y)	45	32
Mean series intercorrelation	0.631	0.255
Chronology standard deviation	0.308	0.314
Chronology autocorrelation	0.203	0.096
Chronology mean sensitivity	0.331	0.303
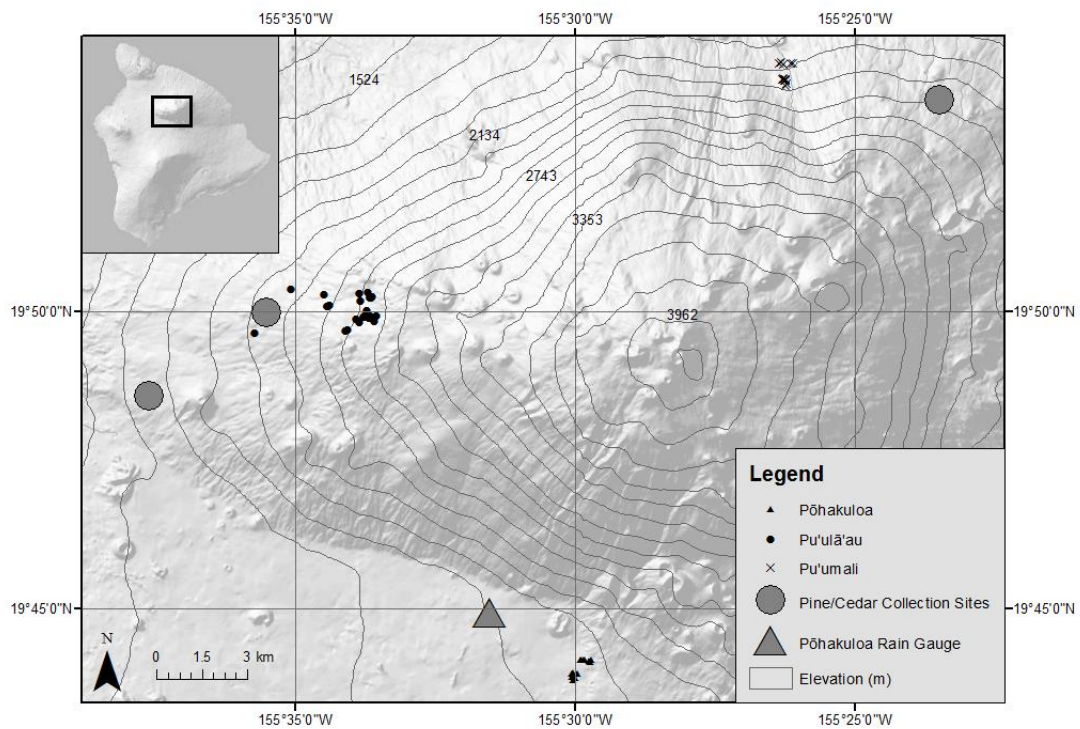
Figure 1. Study site map of Maunakea, Hawaiʻi. Cross-sections were obtained from dead *Sophora chrysophylla* trees at three sites on various slopes of Maunakea - Puʻulāʻau (n = 29), Puʻumali (n = 15), and Pōhakuloa (n = 15). Increment cores were obtained from nearby conifer populations of *Pinus radiata*, *Pinus jeffreyi*, and *Cedrus deodara* from the western (n = 14) and northeastern (n = 10) slopes of Maunakea. Local precipitation data were gathered from a rain gauge station at 1986 m asl in the Pōhakuloa site operated by the Hawaiʻi State Division of Forestry and Wildlife (SKN #107).

1
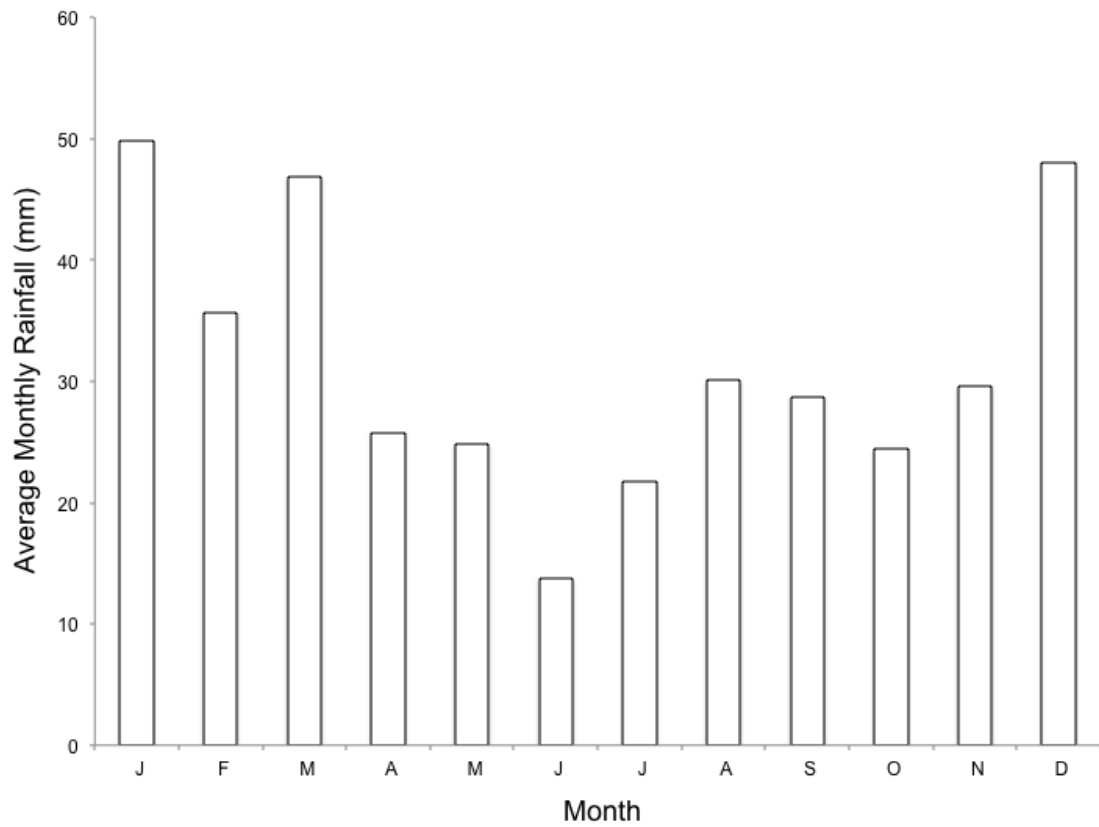
Figure 2. Average monthly rainfall (mm) from a 1986 m asl rain gauge station at

Pōhakuloa, Hawaiʻi (SKN #107, 19°44'55" N, 155°31'32" W) during 1938-1976
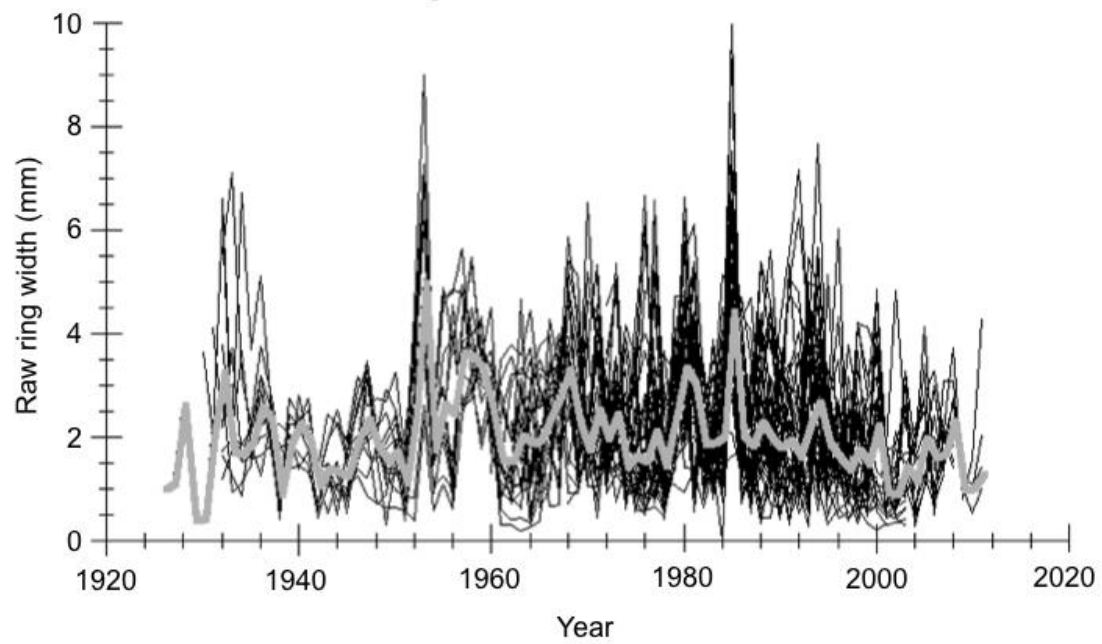
(Giambelluca *et al.* 2011).

Figure 3. Raw tree-ring series (n = 52) and the mean of all series (thick, grey curve) from 15 cross-sections and 7 unpublished, previously dated series of *Sophora chrysophylla* from Pōhakuloa, Hawaiʻi.
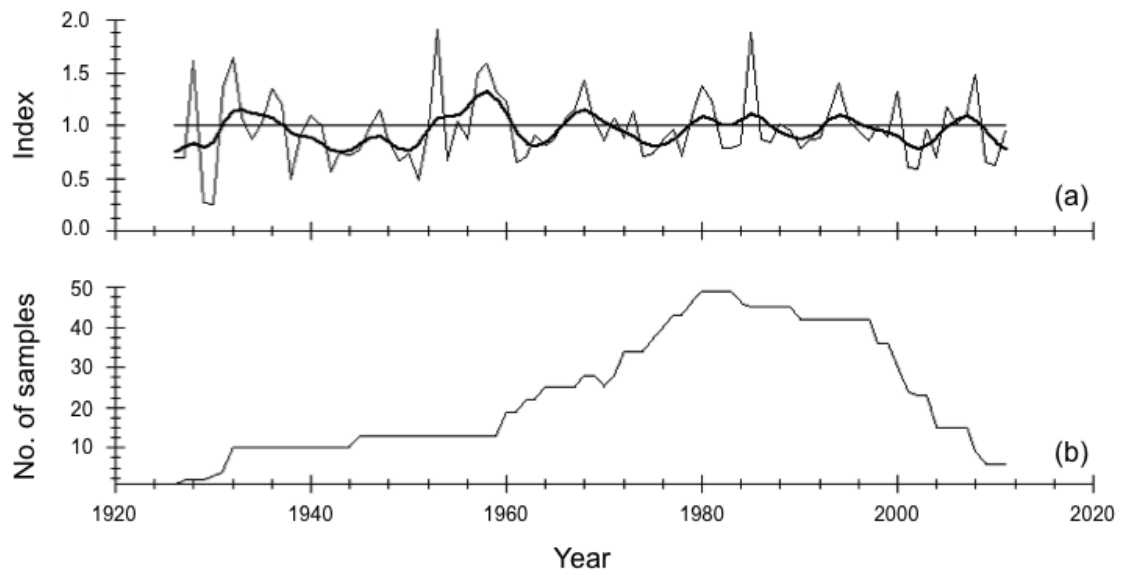
Figure 4. Raw tree-ring series mean and detrended curve (thick, black curve) of an 86-y chronology (1926-2011) of *Sophora chrysophylla* from Pōhakuloa, Hawaiʻi based on 15 cross-sections and 7 unpublished, previously dated series of *S. chrysophylla* (a). Number of samples used to produce the chronology (b).
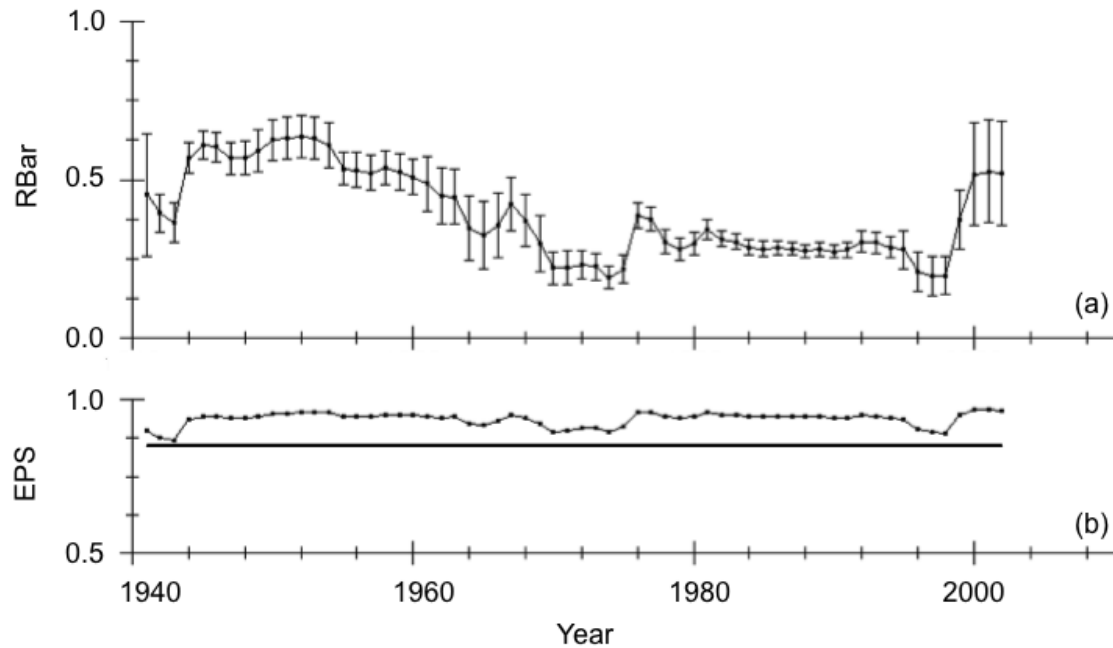
Figure 5. Detrended RBar, with a 20-y window and a 19-y overlap, and Expressed Population Signal (EPS) values of an 86-y chronology (1926-2011) of *Sophora chrysophylla* from Pōhakuloa, Hawaiʻi based on 15 cross-sections and 7 unpublished, previously dated series of *S. chrysophylla*. RBar is a measure of the strength of the common growth signal within a chronology (Wigley *et al.* 1984). This graph shows a relatively strong common signal for the chronology, with the least amount of variation in signal strength, expressed by smaller error bars, from the 1970s to the late 1990s indicating a stronger common signal amongst the samples for that time period (a). Expressed Population Signal (EPS) is a measure of the common variability within a chronology in relation to sample depth (Wigley *et al.* 1984). A chronology with an EPS value greater than or equal to 0.85 can be reliably used for climate analysis (Wigley *et al.* 1984). The EPS values for the Pōhakuloa *S. chrysophylla* chronology are above the 0.85 level (thick, black line). These statistics indicate that this chronology is reliable, and can be used in climate change or ecological studies (b).
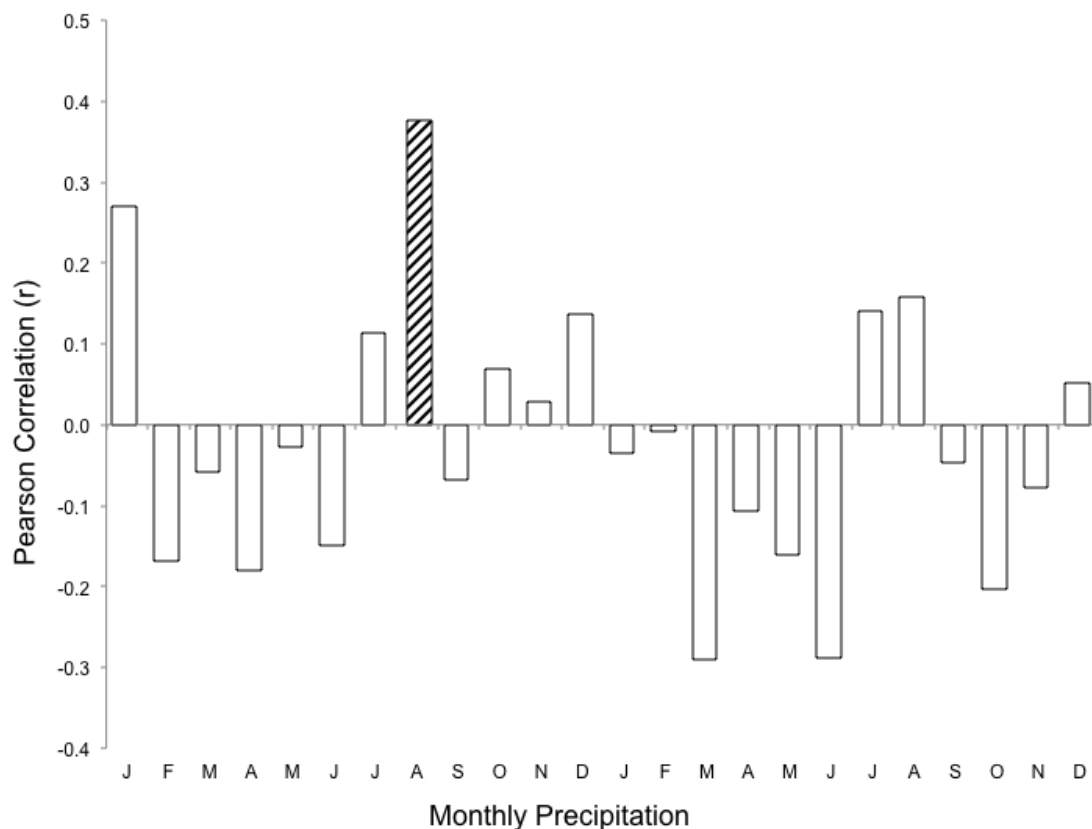
Figure 6. A comparison between local precipitation data (1938-1976) and an 86-y

chronology, spanning from 1926-2011, of *Sophora chrysophylla* from Pōhakuloa,

Hawaiʻi. A Pearson correlation analysis was conducted on the current year's tree-ring

width and the monthly precipitation within the present year, as well as the previous

year (1-y lag). Results indicate that rainfall from the previous August is a significant

predictor of growth, highlighted in the graph by the striped bar ($r = 0.377$, p = 0.019).